RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF THE EFFECTIVENESS OF VARIOUS SUCTION-SLOT ARRANGEMENTS AS A MEANS FOR INCREASING THE MAXIMUM LIFT OF THE NACA 65_3-018 AIRFOIL SECTION

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

In the early part of 1945 a short wind-tunnel investigation was made to explore the possibility of employing boundary-layer suction slots as means for delaying laminar separation at the leading edge and turbulent separation over the rear portions of an airfoil section at high lift coefficients. The airfoil employed in the investigation was a plain NACA 65_3-018 section. The investigation was made at a Reynolds number of 1.0×10^6. Through control of turbulent separation, the maximum lift coefficient was increased from 1.06 to about 1.6. By controlling both laminar and turbulent separation, the maximum lift coefficient was increased to 2.02. Further increases in maximum lift were not possible because the laminar separation point moved ahead of the narrow leading-edge suction slot. If large increments in maximum lift are to be obtained through control of leading-edge separation, a relatively wide slot is required. The proper location of the slot depends to some extend upon the Reynolds number. The amount of suction power required to obtain the increases in maximum lift was relatively high. For example, in order to obtain a maximum lift coefficient of 1.9, a flow coefficient of 0.034 was required and the corresponding drag coefficient equivalent of the suction power was 0.33. The possible effects upon the lift results of increasing the Reynolds number are briefly discussed.

INTRODUCTION

An exploratory investigation of the use of suction slots as a means of delaying separation of the boundary layer on the NACA 65_3-018 airfoil section has been made. The first phase of the investigation, reported in reference 1, consisted of tests of the airfoil section with suction slots located so as to delay separation of the turbulent boundary layer at the rear of the airfoil. The results of the investigation indicated that although the suction slots were effective in delaying separation of the turbulent boundary layer, separation of the laminar layer in the immediate vicinity of the leading edge ultimately limited the maximum obtainable lift coefficient.

The purpose of the latter phase of the investigation, reported herein, was to explore the possibility of using boundary-layer control for delaying separation of the laminar boundary layer near the leading edge. Lift, drag, and internal pressure-loss measurements at various flow coefficients were made for the NACA 65_3-018 airfoil section with a suction slot near the leading edge in addition to two suction slots farther back. The investigation was made at a Reynolds number of 1.0×10^6. The data obtained at this value of the Reynolds number do not give a quantitative representation of the effectiveness of leading-edge boundary-layer control in improving the maximum lift at flight values of the Reynolds number. The results do, however, indicate some of the important design parameters which must be considered in the application of a suction slot for the control of laminar separation.

The tests described in the present paper were made in the early part of 1945.

SYMBOLS AND COEFFICIENTS

b	span over which boundary-layer control is applied, feet
c	airfoil chord, feet
d	section drag, pounds per unit span
l	section lift, pounds per unit span
Q	volume rate of air flow through suction slot, cubic feet per second
H_o	free-stream total pressure, pounds per square foot
H_b	total pressure in wing duct, pounds per square foot
V_o	free-stream velocity, feet per second

ρ_o	mass density, slugs per cubic foot
q_o	free-stream dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho_o V_o^2\right)$
α_o	section angle of attack, degrees
η_b	combined duct and blower efficiency
η_p	efficiency of main propulsive unit
μ	coefficient of viscosity, pound-seconds per square foot
c_{d_o}	section profile-drag coefficient $\left(\frac{d}{q_o c}\right)$
c_{d_b}	blower drag coefficient $\left(C_{Q_1}C_{P_1} + C_{Q_{45}}C_{P_{45}} + C_{Q_{75}}C_{P_{75}}\right)$
c_{d_T}	section total-drag coefficient $\left(c_{d_o} + \left(\frac{\eta_p}{\eta_b}\right)c_{d_b}\right)$
c_l	section lift coefficient $\left(\frac{l}{q_o c}\right)$
$c_{l_{max}}$	maximum section lift coefficient
C_Q	flow coefficient $\left(\frac{Q}{V_o cb}\right)$
C_{Q_T}	total flow coefficient $\left(C_{Q_1} + C_{Q_{45}} + C_{Q_{75}}\right)$
C_P	pressure-loss coefficient $\left(\frac{H_o - H_b}{q_o}\right)$
R	Reynolds number $\left(\frac{\rho_o V_o c}{\mu}\right)$

Subscripts:

1	at 1 percent of airfoil chord
45	at 45 percent of airfoil chord
75	at 75 percent of airfoil chord

MODEL AND TESTS

The tests were made in the Langley two-dimensional low-turbulence tunnel. The test section of this tunnel is $7\frac{1}{2}$ feet by 3 feet with the model, when mounted, completely spanning the 3-foot dimension. The gaps between the ends of the model and the tunnel walls were sealed to prevent air leakage. Lift measurements were obtained by taking the difference between the integrated pressure reactions upon the ceiling and floor of the tunnel. Drag measurements were made by the wake-survey method. A more complete description of the tunnel and the methods of obtaining and correcting the data is contained in reference 2.

Model.- The 3-foot-chord wooden model of the NACA 65_3-018 airfoil section was the same as that employed in the investigation reported in reference 1. Ordinates of the airfoil are given in table I. In the present investigation, the slots at the 45-percent-chord and 75-percent-chord stations were used in combination with a slot at the leading edge. Details of the model and slots are shown in figure 1. The air from each slot was ducted to a venturi meter for measuring the amount of air removed by the blower. The defect in total pressure of the boundary-layer air removed was measured by static-pressure orifices in each duct. The use of static-pressure orifices was justified since only low velocities existed within the ducts.

Tests.- The lift, drag, and internal-pressure-loss data for the airfoil with the various slot combinations were obtained to determine the effectiveness of boundary-layer control in delaying separation. The flow coefficient for the leading-edge slot, 0.01c location, was held at approximately 0.009 and the flow coefficients for the rear slots, 0.45c and 0.75c locations, were varied from 0.003 to 0.016 per slot. The section lift characteristics of the plain airfoil were obtained with the slots sealed and faired. The tests were made at a Reynolds number of 1.0×10^6 because limitations of the available blower equipment made it possible to maintain the desired leading-edge-slot flow coefficient only at a relatively low tunnel airspeed.

A test was made at a Reynolds number of 1.9×10^6 with sealed slots and also with a rough leading edge for comparison with data of reference 1 to determine any effects of roughness due to the leading-edge-slot fairing on the section lift characteristics.

RESULTS AND DISCUSSION

Lift

Effect of leading-edge seal.- Before the effectiveness of the boundary-layer control in improving the maximum lift at a Reynolds number of 1.0×10^6 can be properly evaluated, it is first necessary to know whether the maximum lift of the plain airfoil as determined from tests of the model with slots sealed was affected by any unfairness that might have been present in the seal of the leading-edge slot. Data relative to this point are contained in figure 2. The results obtained in the present tests at a Reynolds number of 1.9×10^6 with all three slots sealed are seen to agree closely with those taken from reference 1 for the airfoil with no slot in the leading edge and the rear slots sealed (fig. 2(a)). Hence, in this case, the seal in the leading-edge slot seemed to approximate with sufficient accuracy the true airfoil contour. With the two rear slots operating at a flow coefficient of 0.011, however, the data from reference 1 in comparison with those obtained in the present investigation indicate that the seal in the front slot was sufficiently unfair or rough as to cause a decrement in maximum lift of 0.1 (fig. 2(b)). The differences in maximum section lift coefficient due to the effect of the seal for the suction and no-suction cases may possibly be attributed to the fact that with suction applied at the 0.45c and 0.75c stations, maximum lift is limited by separation near the leading edge, in which case the effect of small surface irregularities in this region may be more pronounced. The decrement of 0.1 is not nearly so large as that caused by leading-edge roughness, as can be seen readily from the comparative data given in figure 2(b) for the rough-surface condition. Whether or not the decrement in maximum lift due to the seal in the front slot (fig. 2(b)) would also be obtained at a Reynolds number of 1.0×10^6 is not entirely clear. In comparing the results obtained in the present investigation (made at a Reynolds number of 1.0×10^6) for the airfoil with all three slots operating and for the airfoil with the front slot sealed and the two rear slots operating, however, it should be recognized that the increment in maximum lift attributable to the leading-edge slot may be somewhat high.

Relative effectiveness of the leading-edge slot.- The data for the airfoil with all slots sealed and for the airfoil with the leading-edge slot sealed and the two rear slots operating at a total flow coefficient of 0.025 are shown in figure 3(a). For comparison, data for flow coefficients of 0.026 and 0.034 with all three slots operating are also shown in figure 3(a). In figure 3(b) are shown the results for the model with a constant flow coefficient of approximately 0.009 in the front slot and various amounts of flow in the rear two slots. The data pertaining to the relative effectiveness of each of the rear slots when employed with the leading-edge slot are shown in figure 3(c). For any given configuration, the total flow removed was nearly independent of angle of attack. The relative amount of flow removed from each slot, however, varied to some extent with angle of attack. Detailed data from which the exact flow coefficient for each slot can be obtained for any angle of attack are given in figures 4 to 6.

The data of figure 3 indicate that a maximum lift coefficient of 1.90 was obtained for a total flow coefficient of 0.034 with all three slots operating; whereas a maximum lift coefficient of 1.06 was obtained for the airfoil without suction. The relative importance of the leading-edge slot in obtaining this increment in maximum lift can be judged from the lift curve obtained for a total flow coefficient of 0.025 with only the rear two slots operating. The data obtained for this configuration, shown in figure 3(a), indicate that the primary effect of suction in the rear slots alone was to straighten the lift curve without increasing the angle of attack for maximum lift. For the flow coefficient of 0.025 in the rear slots alone, the rounded lift curve obtained in the no-suction case is seen to be completely linearized with an abrupt loss in lift occurring at the stall. This type of stall is indicative of laminar separation near the leading edge. Tuft studies also indicated that separation at the leading edge limited the lift. Consequently, the use of a total flow coefficient greater than 0.025 in the rear slots alone would not be expected to result in any substantial increases in maximum lift above the value of 1.6 obtained in this case. It is, of course, possible that if boundary-layer control at the leading edge delays laminar separation so that the maximum lift coefficient is increased by an extension of the lift curve to higher angles of attack, more suction will be required in the rear slots to prevent any turbulent separation which might result from the increased pressure recovery over the airfoil. The data of figure 3 indicate that some such effect as this occurred on the NACA 65_3-018 airfoil. With a flow coefficient of about 0.009 in the leading edge in addition to the flow coefficient of 0.025 in the rear slots $\left(C_{Q_T} = 0.034\right)$, the lift curve was extended with a corresponding increase in maximum lift from 1.6 to 1.9 (figs. 3(a) and 3(b)). The lift curve corresponding to this total flow coefficient is seen, however, to be slightly rounded near maximum lift. Increasing the flow coefficient in the rear slots to 0.032 $\left(C_{Q_T} = 0.041\right)$ while maintaining a flow coefficient of approximately 0.009 in the leading-edge slot straightened the lift curve and increased the maximum lift coefficient from 1.9 to 2.02 (fig. 3(b)). From this discussion, it is apparent that although some of the increment in maximum lift coefficient from 1.6 to 2.02 resulted from an increase in flow removal in the rear slots after the front slot was put in operation, no portion of the increment (0.42) in maximum lift would have been obtained without the leading-edge slot. It should be remembered that the increment in maximum lift attributable to the leading-edge slot may be as much as 0.1 smaller than the value of 0.42 shown by the data because of the possible effect of the leading-edge seal on the maximum lift of the airfoil with only the rear two slots operating.

For a total flow coefficient of 0.041, tuft studies indicated that the stall occurred when laminar separation developed ahead of the relatively small leading-edge slot. Consequently, for the particular suction-slot configuration employed, the lift curve probably could not have been extended to any higher angle of attack by the use of total flow coefficients greater than 0.041. In order to delay laminar separation through a range of angle of attack sufficient to permit larger gains in maximum lift, the suction slot should be sufficiently wide so as to encompass the movement of the laminar separation point with angle of attack. This is in agreement with the results discussed in reference 3 which show that a wide slot at the leading edge is more effective in increasing the maximum lift than a small one.

<u>Relative effectiveness of the two rear slots</u>.- The data of figures 3(b) and 3(c) indicate that for a given total flow rate either the 0.45c or 0.75c slot operated in combination with the leading-edge slot was as effective in increasing lift as was the combination of both rear slots with the leading-edge slot. In fact, the use of the slot at 0.45c in combination with the leading-edge slot at a total flow coefficient of 0.020 resulted in a maximum section lift coefficient that was slightly higher than that obtained by using all three slots at a total flow coefficient of 0.026.

<u>Effect of Reynolds number</u>.- A comparison of the maximum lift data obtained in the investigation of reference 1 with those obtained in the present investigation (fig. 7) indicates that increasing the Reynolds number from 1.0×10^6 to 6.0×10^6 has a relatively large favorable effect on the maximum lift coefficient. This comparison would seem to indicate that had the investigation of the three suction slots been made at a higher Reynolds number, maximum lift coefficients somewhat higher than 2.02 might possibly have been obtained. It is very doubtful, however, that any increases in the maximum lift of the airfoil with the two rear slots at Reynolds number of 1.9×10^6 and 6.0×10^6 would be

obtained by using the leading-edge slot employed in this investigation. An examination of the data of figures 2(b) and 3(a) indicates that, with the two rear slots operating, the increase in maximum lift which accompanies an increase in Reynolds number from 1.0×10^6 to 1.9×10^6 results from an extension of the lift curve to higher angles of attack. Consequently, at a Reynolds number of 1.9×10^6, the laminar separation point is probably ahead of the location of the narrow slot when the stall occurs. If such is the case, applying suction through the leading-edge slot would not be expected to improve the maximum lift. The proper location of a suction slot designed to delay leading-edge separation would seem to depend to some extent upon the Reynolds number. As previously pointed out, the use of a relatively wide slot is desirable.

Drag

The amount of suction power required to produce a certain aerodynamic improvement is a primary consideration in any application of boundary-layer control. In order to show the suction-power requirements associated with the methods of boundary-layer control considered in the present investigation, the pressure-loss and quantity flow data obtained are presented in figures 8 and 9 in the form of the drag coefficient equivalent of the suction power. Also included in figures 8 and 9 are data giving the total-drag coefficient. The total-drag coefficient was taken as the sum of the external-drag coefficient and the drag coefficient equivalent of the suction power. This method of obtaining the total-drag coefficient is shown in reference 4 to be valid if the efficiency of the boundary-layer control system is equal to the efficiency of the main propulsive unit of an aircraft. The external-drag values obtained for the various boundary-layer control configurations are shown in figure 10.

An examination of the data of figures 8 to 10 indicates that although very low external-drag coefficients are obtained with the use of boundary-layer control, the values of the drag coefficients equivalent of the suction power are extremely high. In some cases, the blower drag coefficient is seen to be as much as 160 times the external-drag coefficient for the same configuration. For the same total flow rate, the use of the three slots more than doubled the blower drag coefficient obtained with the use of only the two rear slots (fig. 9(a)). Some reduction in the blower drag, however, may possibly be obtained by the use of slots of different shapes than those employed.

For slots of equal size and shape, the data of figure 9(b) in comparison with those of figure 8 show that a given quantity of flow can be removed through two slots with less power than through one slot. The necessarily higher inlet-velocity ratio associated with the use of a single slot, of course, explains this result.

An indication of the meaning of the high blower drag coefficients in terms of the power required in an actual airplane can easily be obtained. A total flow coefficient of 0.034 is seen to give a maximum lift coefficient of 1.9 (fig. 8). If an airplane having a wing loading of 50 pounds per square foot is assumed, a landing speed of about 107 miles per hour at sea level is obtained for a lift coefficient of 0.9 of the maximum lift coefficient of 1.9. The corresponding power required for the boundary-layer-control equipment is found to be 2.2 horsepower per square foot $\left(c_{d_T} = 0.33\right)$. This means that for an airplane the size of a twin-engine transport which might perhaps have a wing area of 800 square feet, a 1760-horsepower engine would be required for the boundary-layer suction equipment. In view of the relatively large increments in maximum lift which can be obtained on an airfoil of 18-percent thickness with a well-designed flap alone or in combination with a midchord suction slot requiring a small expenditure of power, it is difficult to see why the particular configurations discussed in the present paper would be employed on an aircraft unless, as in the case of the all-wing airplane, the large pitching moments associated with a powerful flap could not be tolerated. It must be remembered that the calculations of the power requirements for the assumed airplane were based on data obtained at a Reynolds number of 1.0×10^6. The data of figure 7 show that, as the Reynolds number is increased, the maximum lift also increases for a given flow rate. Consequently, the suction power required at minimum speed for an airplane of given wing loading will decrease to some extent with increasing Reynolds number.

It might also be pointed out that the maximum lift coefficients of airfoils of the order of 6 to 10 percent in thickness are definitely limited to relatively low values by leading-edge separation. For such airfoils, the use of both leading-edge and trailing-edge high-lift devices oftentimes does not yield sufficiently high maximum lift coefficients. In these cases, it is possible that a properly designed application of boundary-layer control at the leading edge may prove of considerable value in spite of the large expenditure of power necessary for any leading-edge application of boundary-layer control.

CONCLUDING REMARKS

By the use of suction slots located at the 1-percent-chord, 45-percent-chord, and 75-percent-chord stations, the maximum lift coefficient of a plain NACA 65_3-018 airfoil was increased from 1.06 to 2.02 with a total flow coefficient of 0.041 at a Reynolds number of 1.0×10^6. With the use of only the 45-percent-chord and 75-percent-chord slot locations to control separation of the turbulent boundary layer, the maximum lift coefficient was limited to a value of the order of 1.6. When the slot at 1-percent chord was employed in conjunction with the other two slots, separation of the laminar layer near the leading edge was delayed and with additional suction in the rear slots the maximum lift coefficient was increased from 1.6 to 2.02. Further increases in the maximum lift coefficient could not be obtained because the laminar separation point moved ahead of the relatively narrow leading-edge slot. If large increments in maximum lift are to be obtained through control of leading-edge separation, a relatively wide slot is required. The proper location of the slot depends to some extent on the Reynolds number. Although the external-drag coefficients of the airfoil with boundary-layer control were small, the total-drag coefficients were very large due to the addition of the suction-power drag coefficients. For example, the drag coefficient equivalent of the suction power required to obtain a maximum lift coefficient of 1.9 was 0.33.

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2. Von Doenhoff, Albert E., and Abbott, Frank T., Jr.: The Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN 1283, 1947.

3. McCollough, George B., and Gault, Donald E.: An Experimental Investigation of an NACA 63_1-012 Airfoil Section with Leading-Edge Suction Slots. NACA TN 1683, 1948.

4. Von Doenhoff, Albert E., and Horton, Elmer A.: Wind-Tunnel Investigation of NACA 65,3-418 Airfoil Section with Boundary-Layer Control through a Single Suction Slot Applied to a Plain Flap. NACA RM L9A20, 1949.

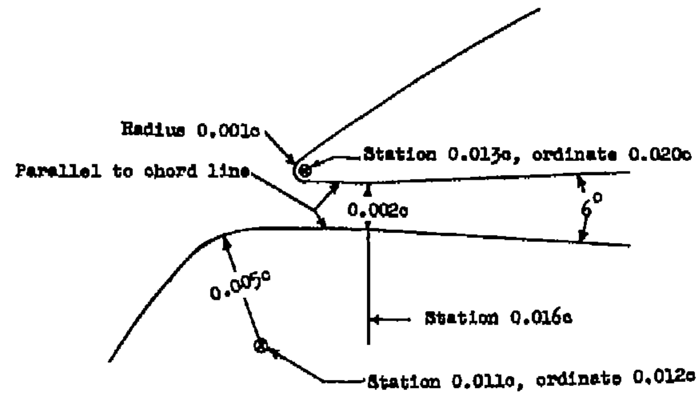
TABLE I

ORDINATES FOR THE NACA 65_3-018 AIRFOIL SECTION

[Stations and ordinates in percent airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.50	1.337	.50	-1.337
.75	1.608	.75	-1.608
1.25	2.014	1.25	-2.014
2.5	2.751	2.5	-2.751
5.0	3.866	5.0	-3.866
7.5	4.733	7.5	-4.733
10	5.457	10	-5.457
15	6.606	15	-6.606
20	7.476	20	-7.476
25	8.129	25	-8.129
30	8.595	30	-8.595
35	8.886	35	-8.886
40	8.999	40	-8.999
45	8.901	45	-8.901
50	8.568	50	-8.568
55	8.008	55	-8.008
60	7.267	60	-7.267
65	6.395	65	-6.395
70	5.426	70	-5.426
75	4.396	75	-4.396
80	3.338	80	-3.338
85	2.295	85	-2.295
90	1.319	90	-1.319
95	.490	95	-.490
100	0	100	0
L.E. radius: 1.96			

NACA



Details of leading-edge slot

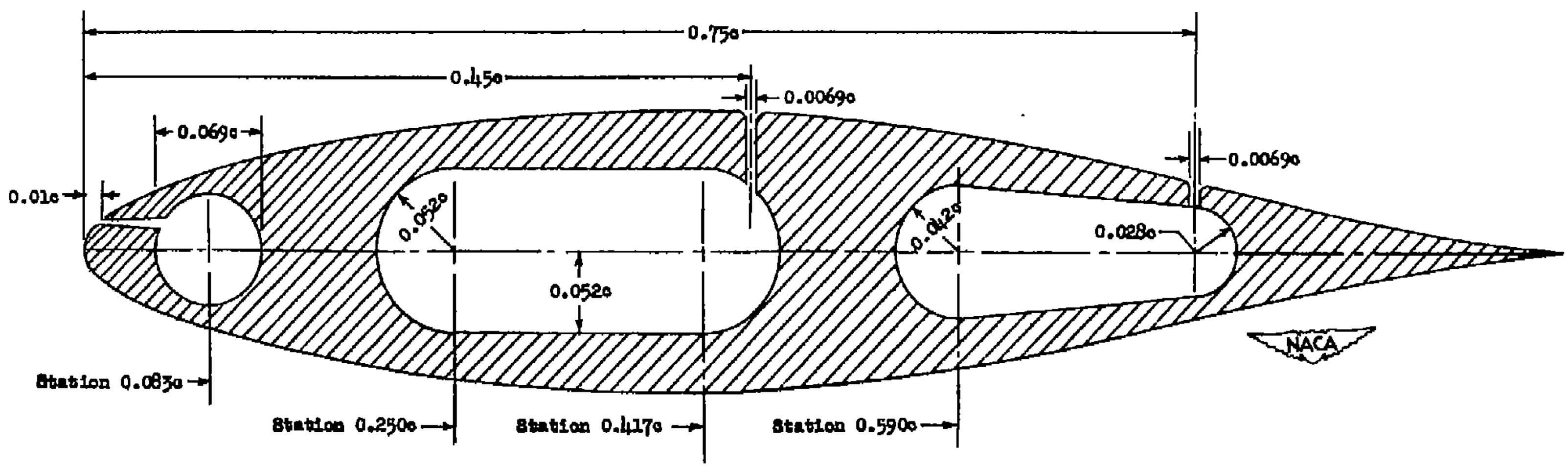
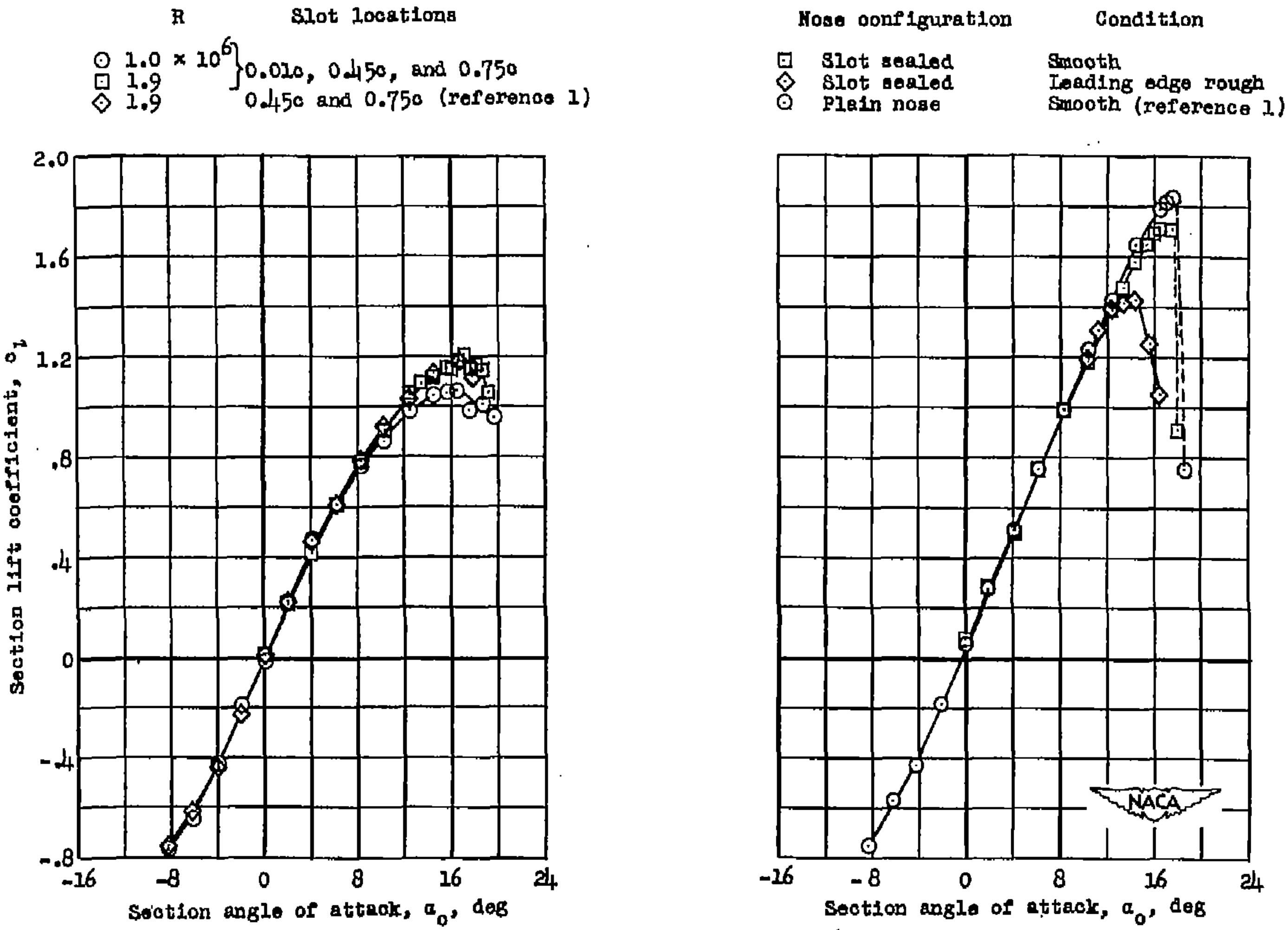


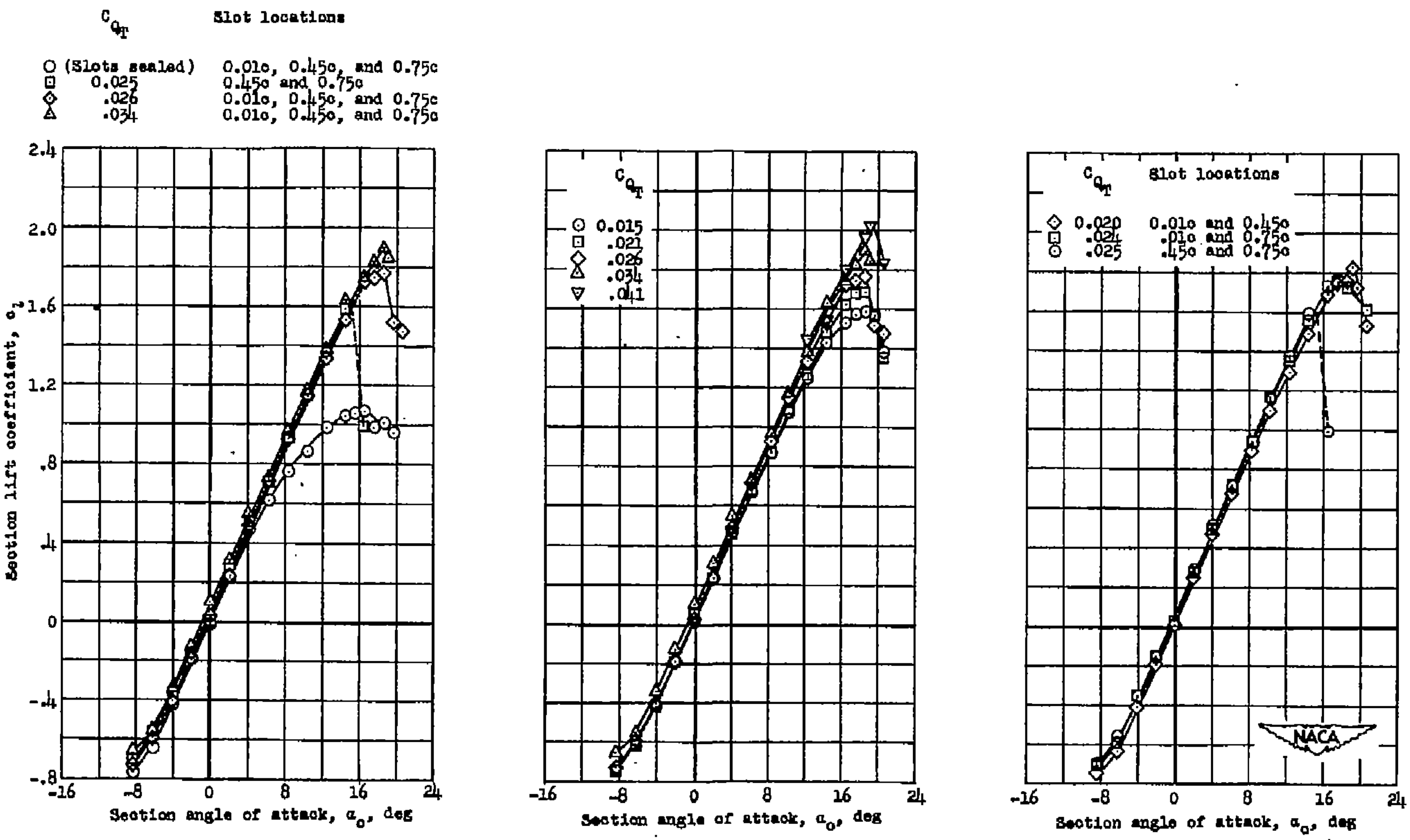
Figure 1.- Profile of the NACA 65_3-018 airfoil section with boundary-layer control slots.



(a) Slots sealed and faired; $C_{Q_T} = 0$.

(b) Slots at 0.45c and 0.75c in operation; $C_{Q_T} = 0.011$ (approx.); $R = 1.9 \times 10^6$.

Figure 2.– Comparison of section lift characteristics of one model of the NACA 65_3-018 airfoil section equipped with three boundary-layer control slots with the model equipped with two boundary-layer control slots.



(a) Comparison of lift for model with no slots and with 2 and 3 slots.

(b) Effect of total flow coefficient on lift of model with slots at 0.01c, 0.45c, and 0.75c.

(c) Comparison of lift for model with various slot combinations.

Figure 3.– Section lift characteristics of the NACA 65_3-018 airfoil section with boundary-layer control slots at 0.01c, 0.45c, and 0.75c. $R = 1.0 \times 10^6$.

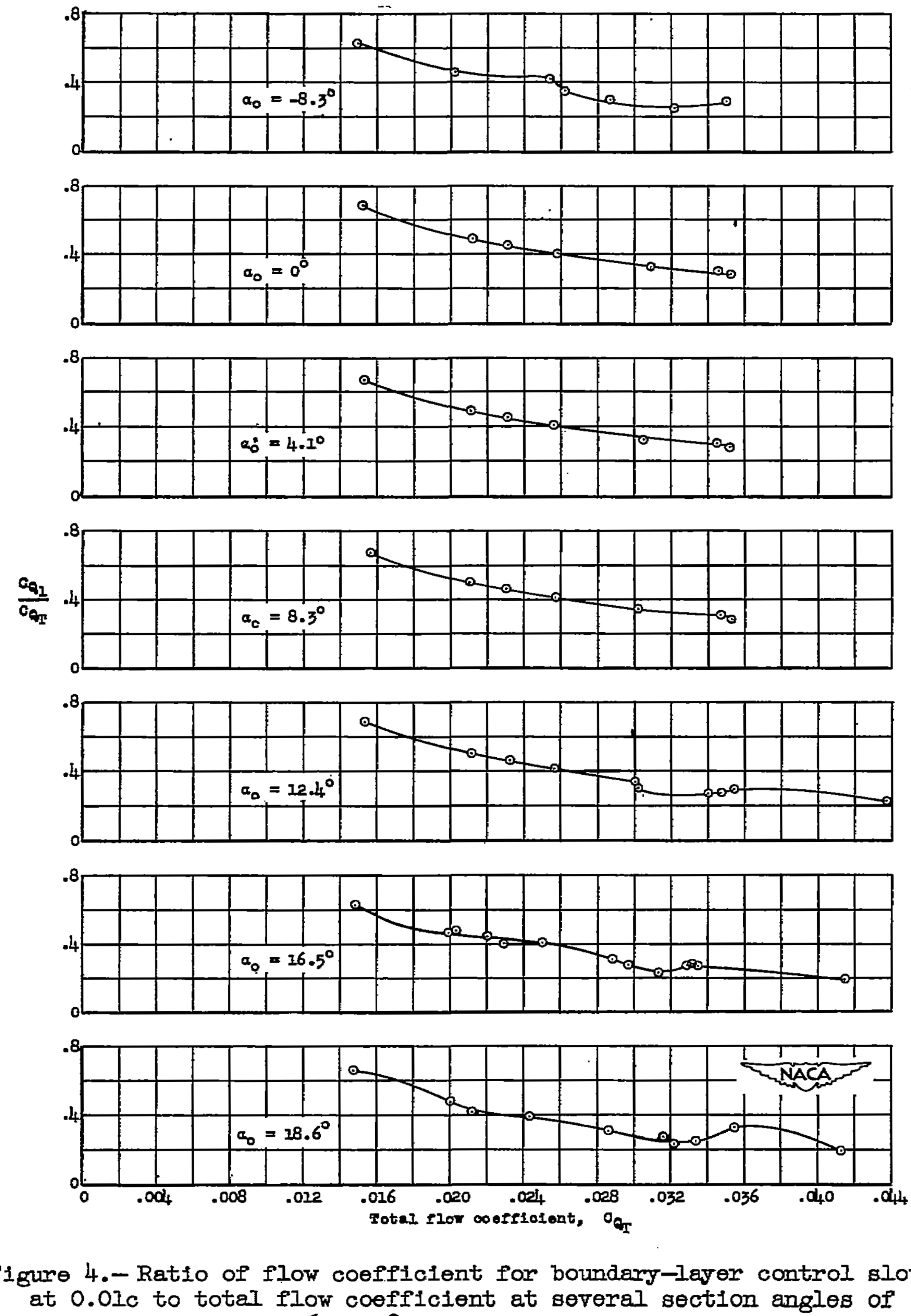


Figure 4.– Ratio of flow coefficient for boundary-layer control slot at 0.01c to total flow coefficient at several section angles of attack for the NACA 65_3-018 airfoil section with boundary-layer control slots at 0.01c, 0.45c, and 0.75c. $R = 1.0 \times 10^6$.

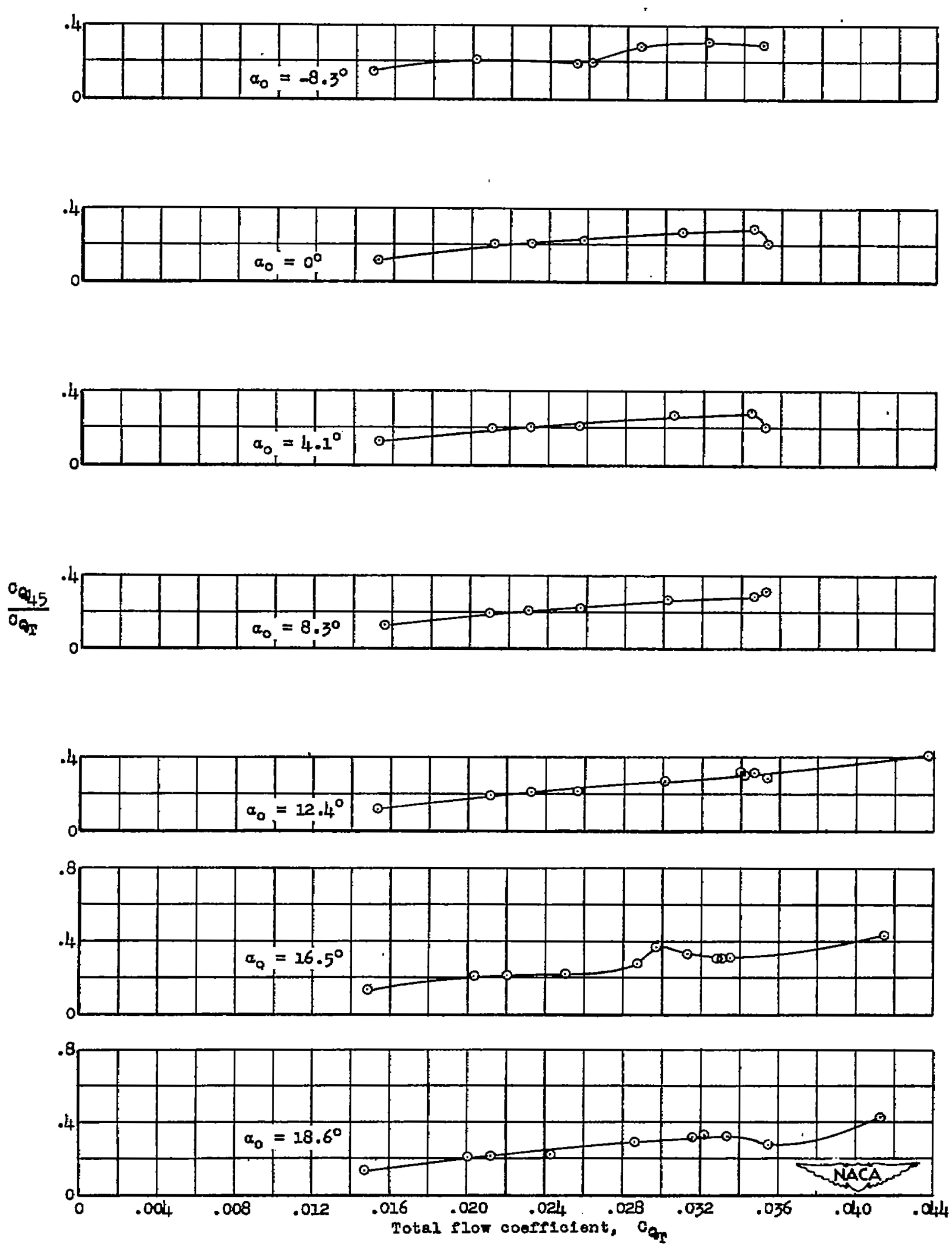


Figure 5.- Ratio of flow coefficient for boundary-layer control slot at 0.45c to total flow coefficient at several section angles of attack for the NACA 65_3-018 airfoil section with boundary-layer control slots at 0.01c, 0.45c, and 0.75c. R = 1.0 × 10^6.

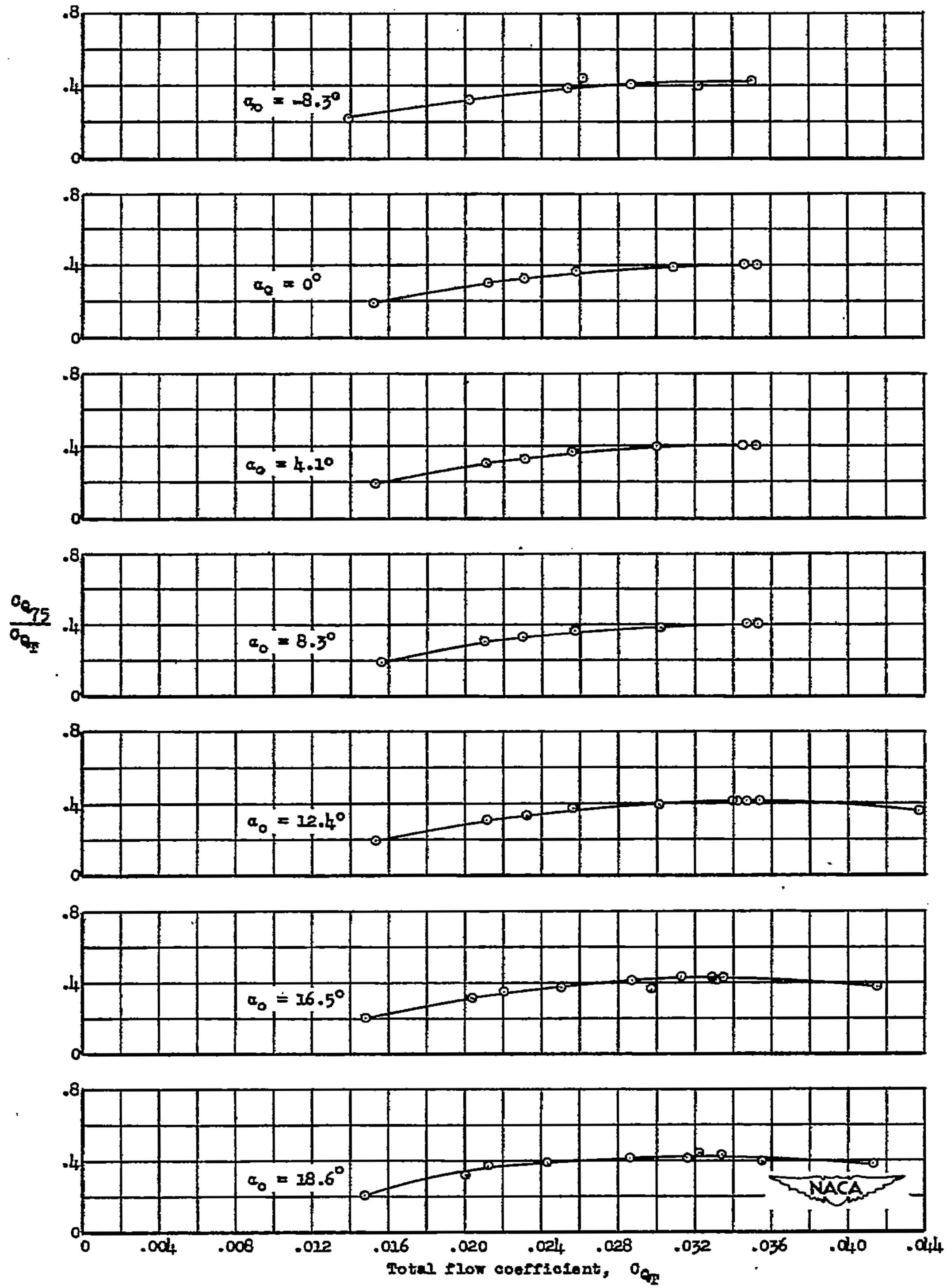


Figure 6.– Ratio of flow coefficient for boundary-layer control slot at 0.75c to total flow coefficient at several section angles of attack for the NACA 65_3-018 airfoil section with boundary-layer control slots at 0.01c, 0.45c, and 0.75c. $R = 1.0 \times 10^6$.

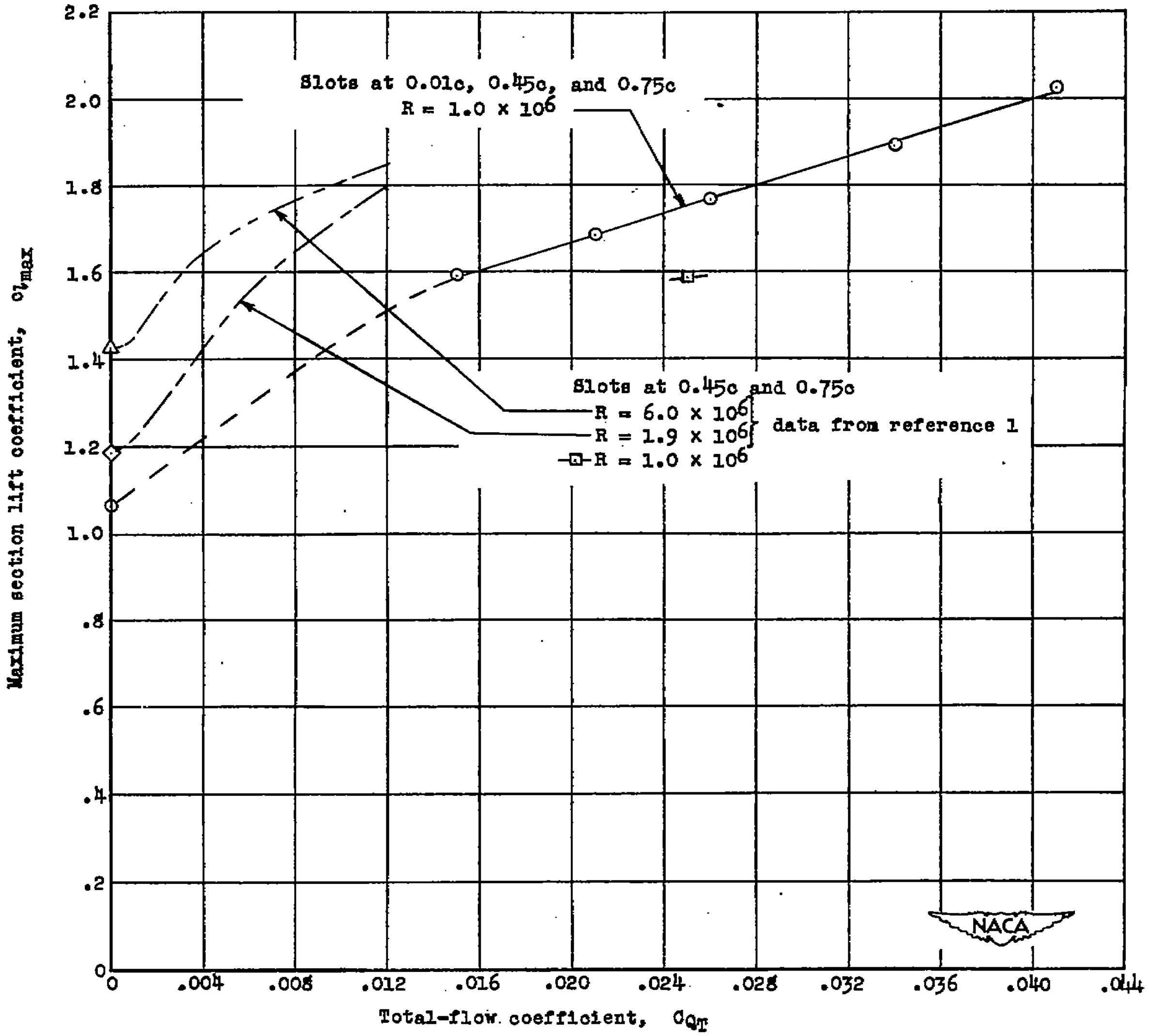
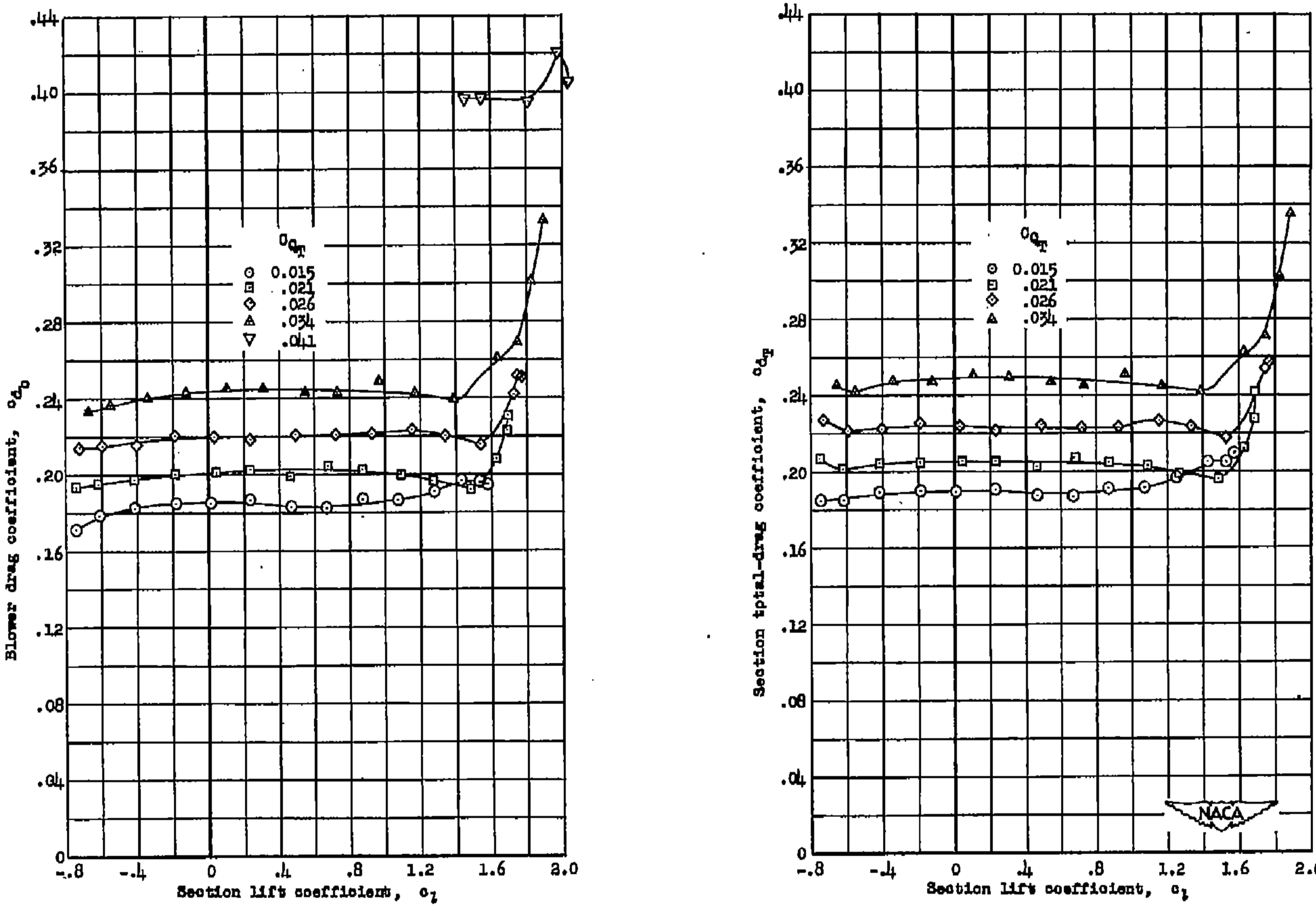


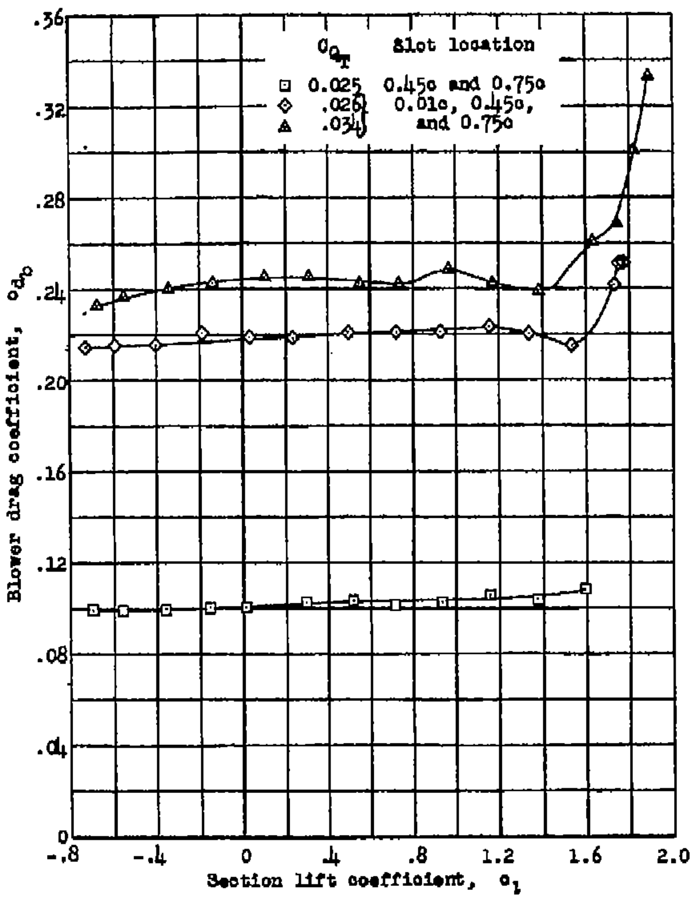
Figure 7.— Variation of maximum section lift coefficient with total flow coefficient for the NACA 65_3-018 airfoil section with three boundary-layer control slots and with two boundary-layer control slots.



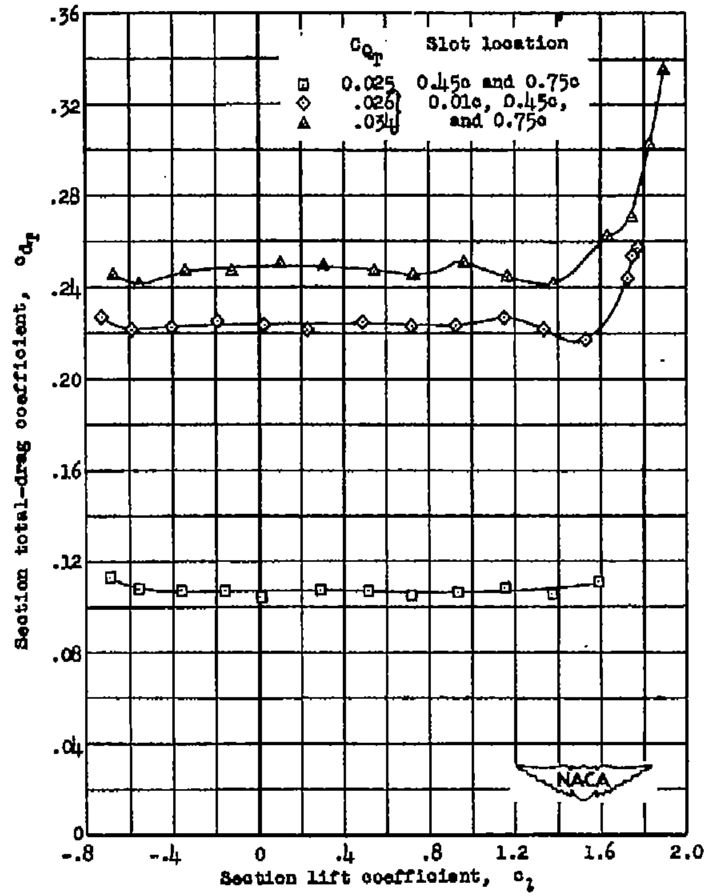
(a) Blower drag characteristics.

(b) Total-drag characteristics.

Figure 8.– Section drag characteristics of the NACA 65_3-018 airfoil section with boundary-layer control slots at 0.01c, 0.45c, and 0.75c. $R = 1.0 \times 10^6$.



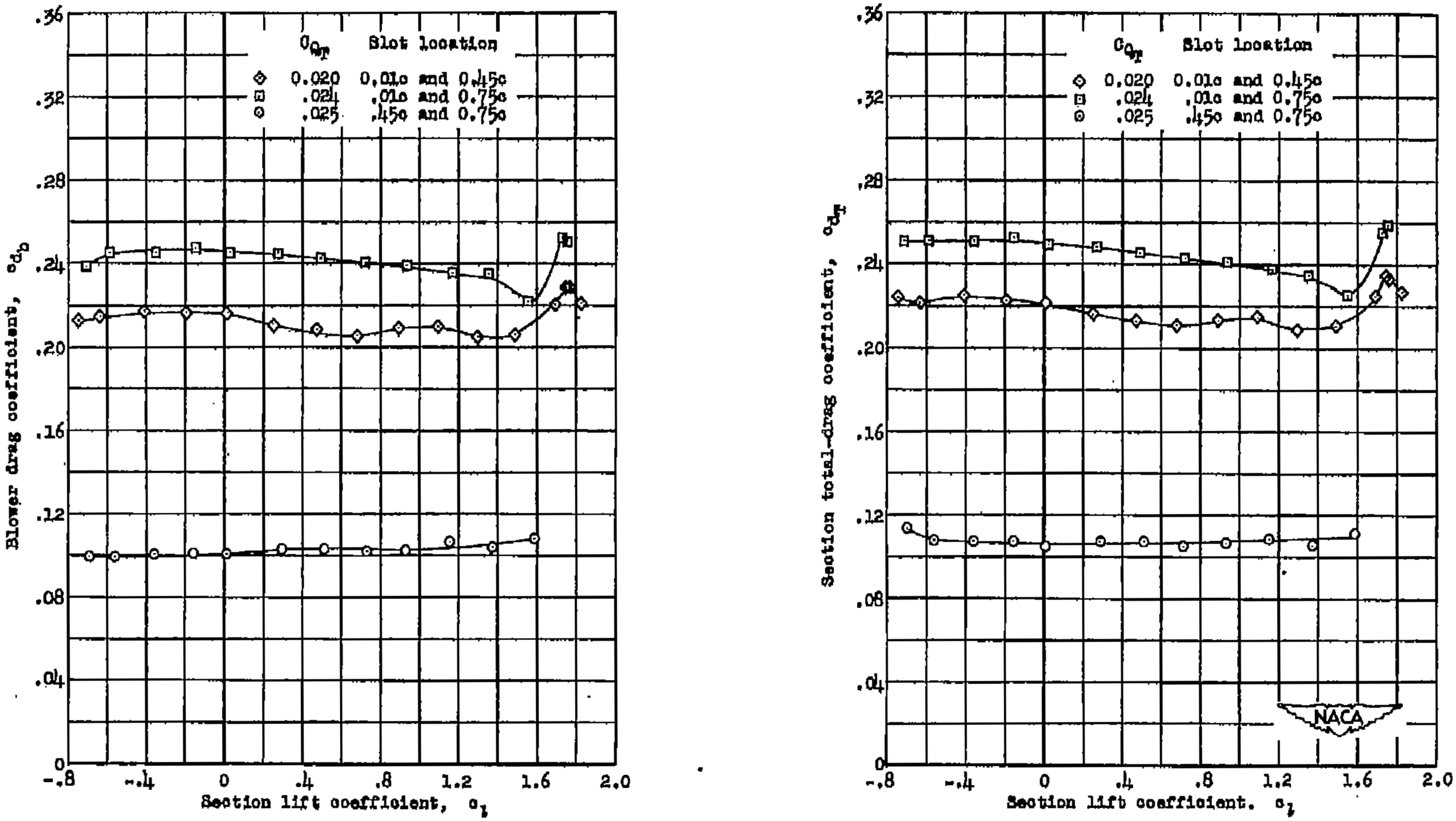
(a) Blower drag characteristics.



(b) Total-drag characteristics.

(a) Model with two and with three slots.

Figure 9.– Section drag characteristics of the NACA 65_3-018 airfoil section with boundary-layer control. $R = 1.0 \times 10^6$.



(a) Blower drag characteristics.

(b) Total-drag characteristics.

(b) Model with any pair of slots.

Figure 9.– Concluded.

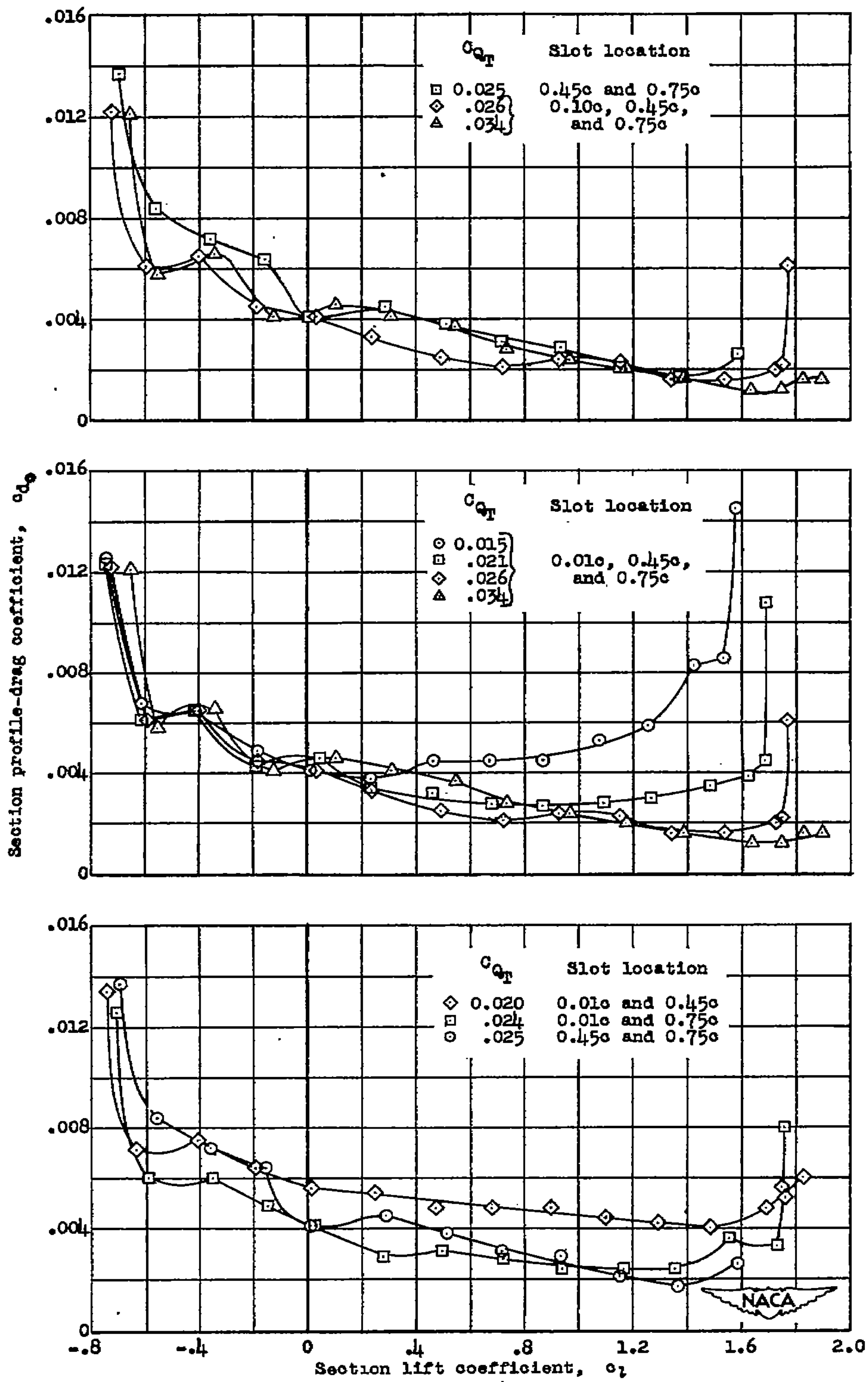


Figure 10.— Section profile-drag characteristics of the NACA 65_3-018 airfoil section with boundary-layer control. $R = 1.0 \times 10^6$.